Strangeness Production and Partonic EoS at RHIC

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Many thanks to organizers

and

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H. Ritter, K. Schweda, P. Sorensen, Z. Xu

P. Huovinen, R. Rapp, K. Redlich, ….

Original Thoughts

Predictions that the strange versus non-strange anti-baryon ratio is a good signal in the baryon-`rich' region are confirmed. …

$gg \Rightarrow ss$

B. Muller, Nucl. Phys. A461, 213(1987)

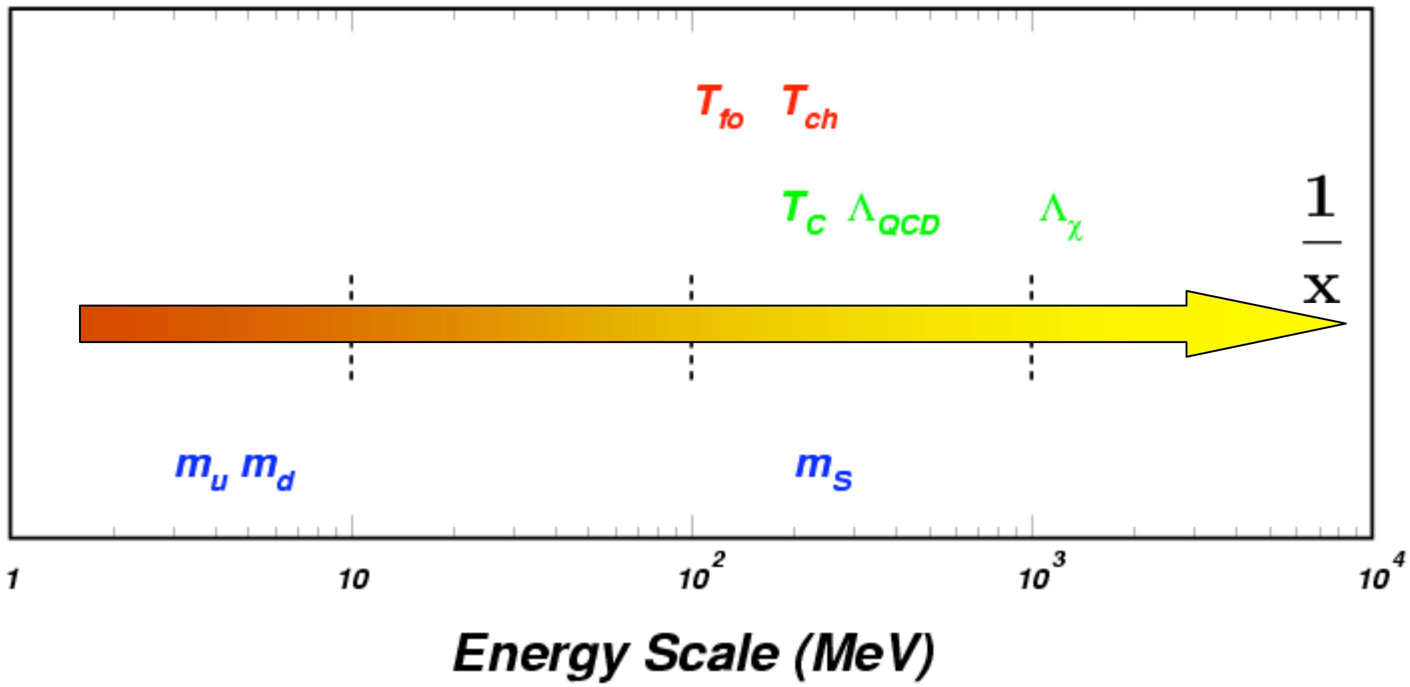
I argue that in the central region, strangeness is not a signal of the existence of a quark-gluon plasma, although an enhanced strangeness production might signal interesting dynamical phenomena. I argue that the strangeness in a quark-gluon plasma compared to that in a hadron resonance gas is not anomalously large for either the K/π ratio or the strange to non-strange anti-baryon ratios.

L. McLerran, Nucl. Phys. A461, 245(1987)

Outline

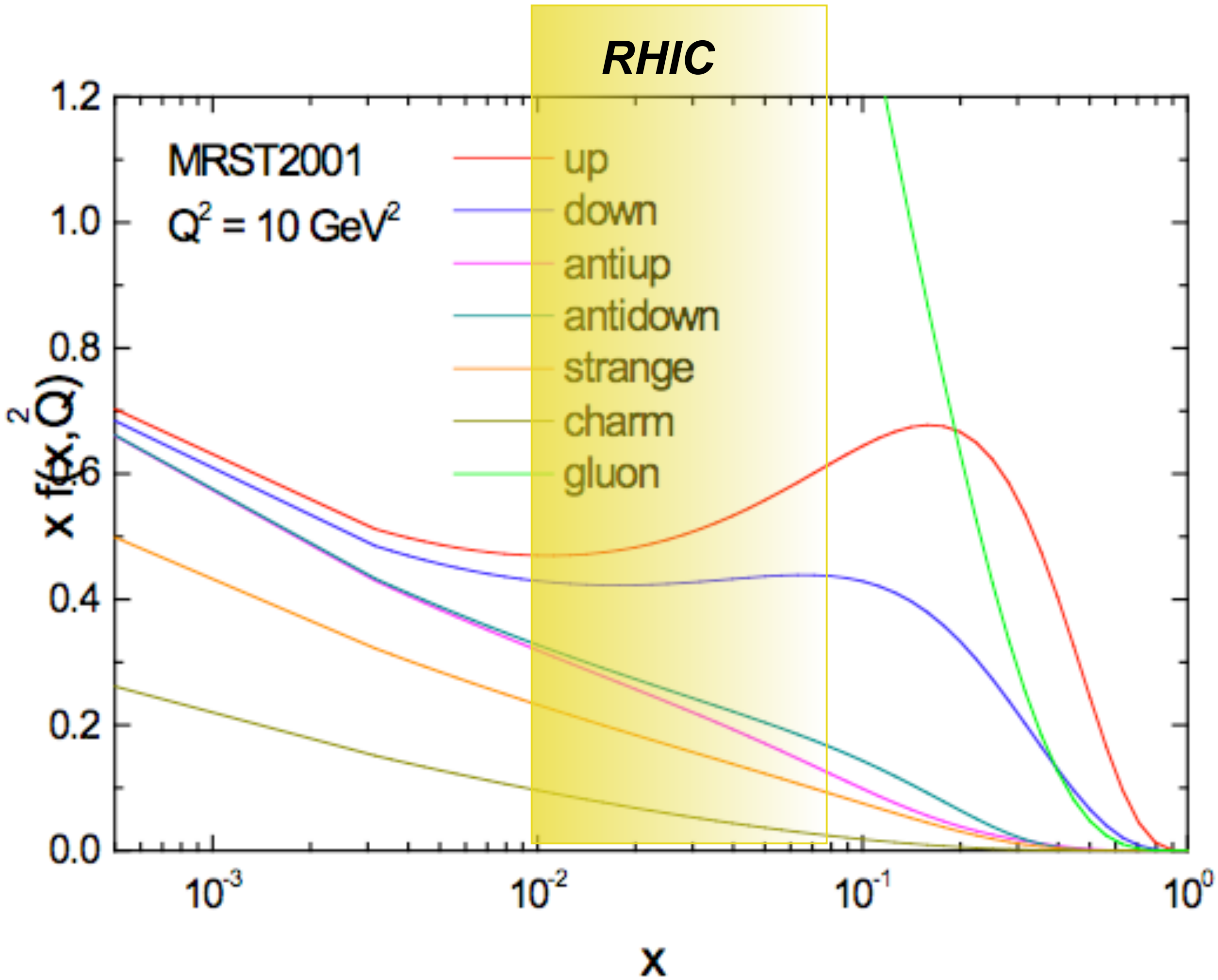
- Motivation
- Strangeness production
- Partonic EOS in high-energy nuclear collisions
- Questions

QCD Energy Scale



m_s ~ 0.2 GeV, similar to values **T_C critical temperature** **Λ_{QCD} QCD scale parameter** **T_{CH} chemical freeze-out temperature** **$\Lambda_\chi = 4\pi f_\pi$ scale for χ symmetry breaking**	**m_c ~ 1.2 - 1.5 GeV >> Λ_{QCD}** **- pQCD production - parton density at small-x** **- QCD interaction - medium properties** **R_{cc} ~ $1/m_C$ => color screening** **J/ψ => deconfinement and thermalization**
u-, d-, s-quarks: ***light-flavors***	c-, b-quarks: ***heavy-flavors***

PDF, RHIC



This plot is copied from an unknown STAR person

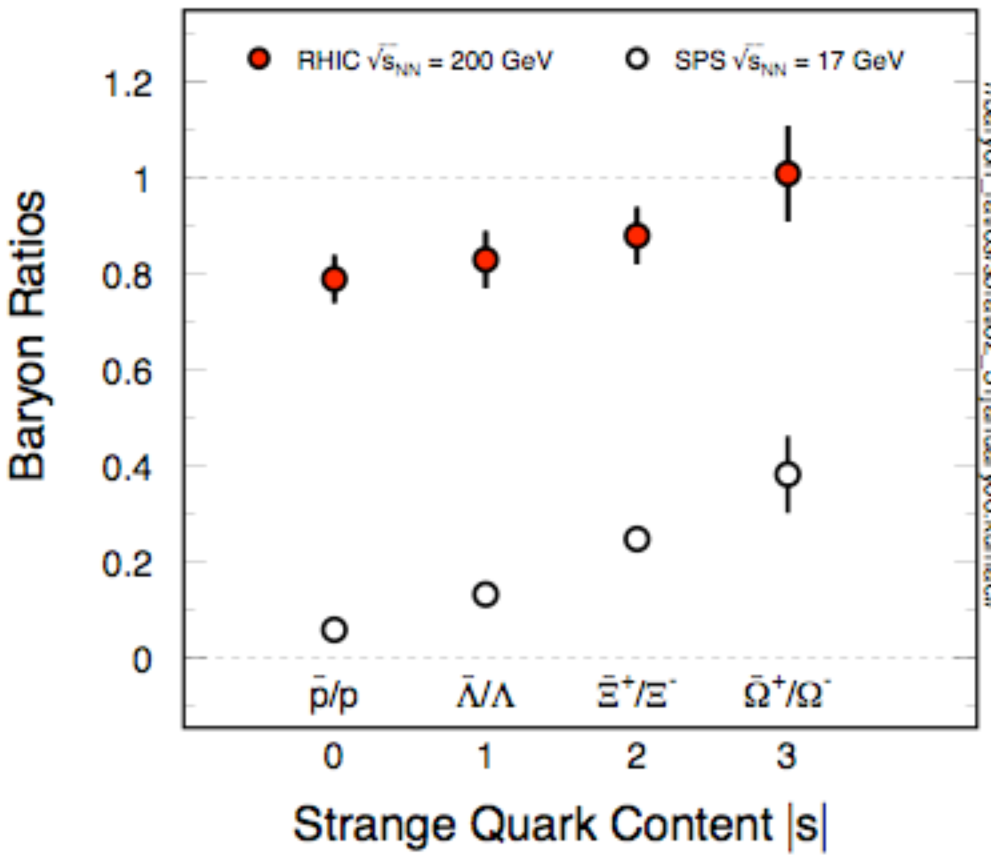
1) In collisions at RHIC, gluons are dominant constituents at the early stage of the interactions*.

2) Strangeness pair productions become important**.

A. Martin, R. Roberts, W. Stirling and R. Thorne, Eur. Phys. J. **C23, 73(2002).*

P. Koch, B. Muller and J. Rafelski, Phys. Report, **142, 167(1986).

Anti-baryon over baryon ratios

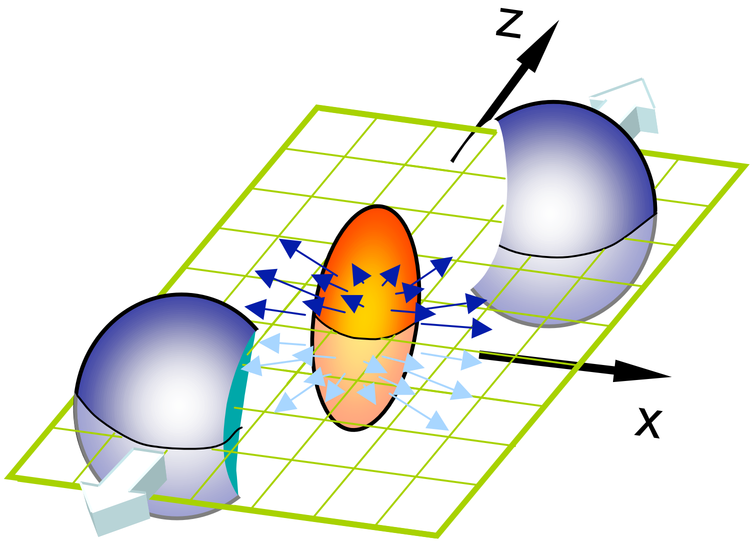


1) Compare to SPS results, the mid-rapidity anti-baryon to baryon ratios are much larger in central Au+Au collisions at RHIC. There is almost no centrality dependence at RHIC.
   ⇒ gluon/sea parton interactions dominant at RHIC.

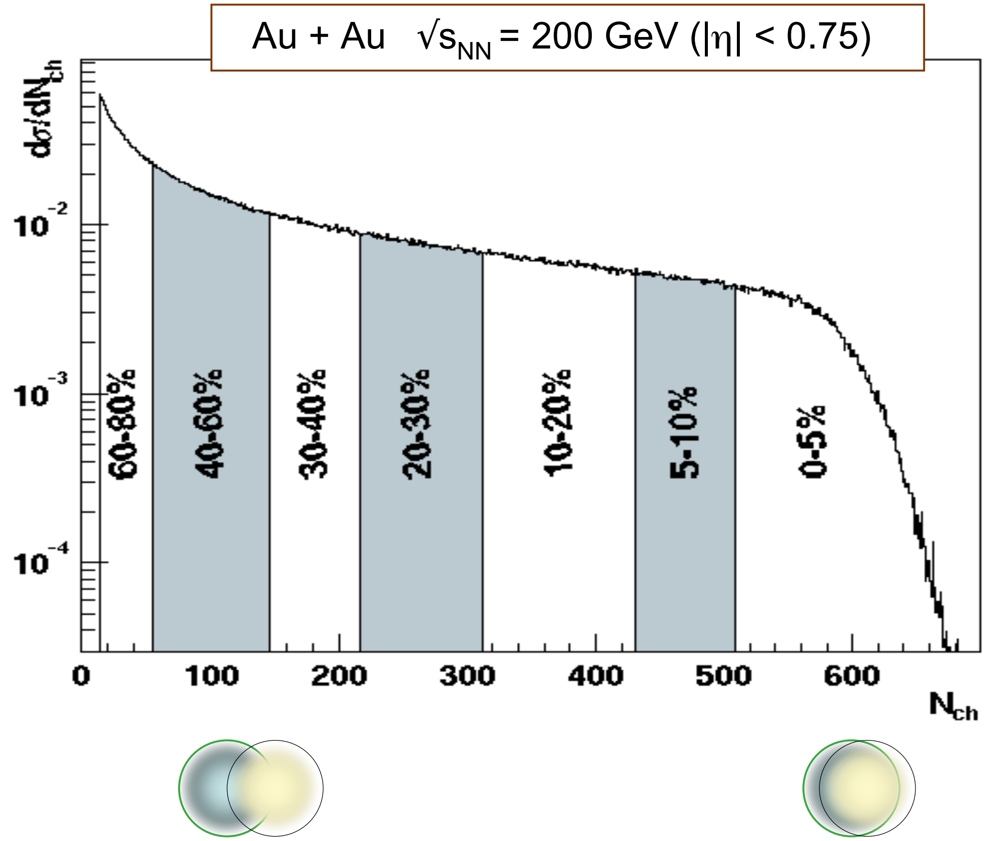
2) The ratio increases according to the hadron strangeness content
   ⇒ more gluon contributions in multi-strange hadron production.

- J. Zimanyi *et al,* hep-ph/0103156
- URQMD: strength color field

Collision Geometry, Flow



Non-central Collisions



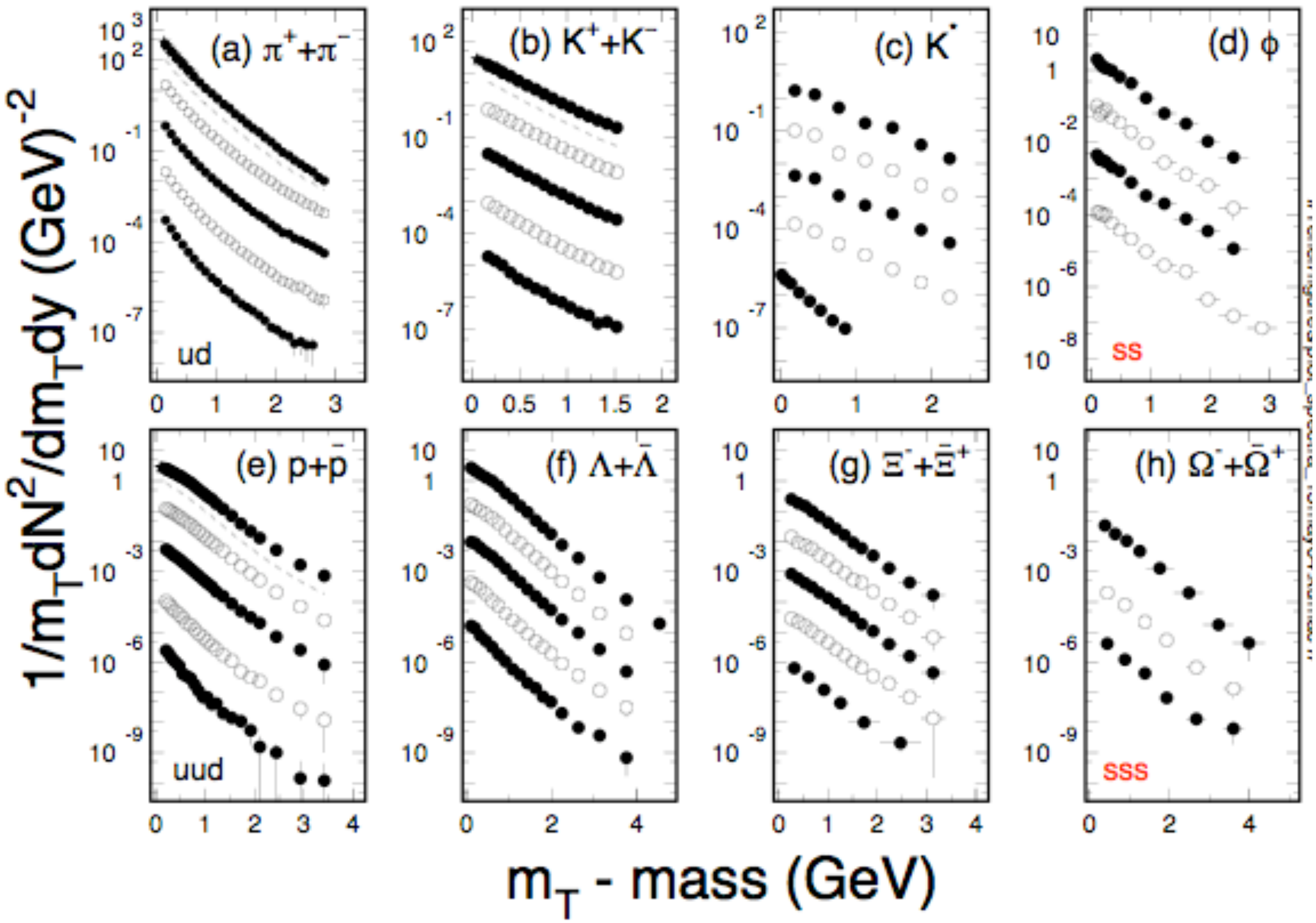
Number of participants: number of incoming nucleons in the overlap region
Number of binary collisions: number of inelastic nucleon-nucleon collisions

Charged particle multiplicity ⇔ collision centrality

Reaction plane: x-z plane

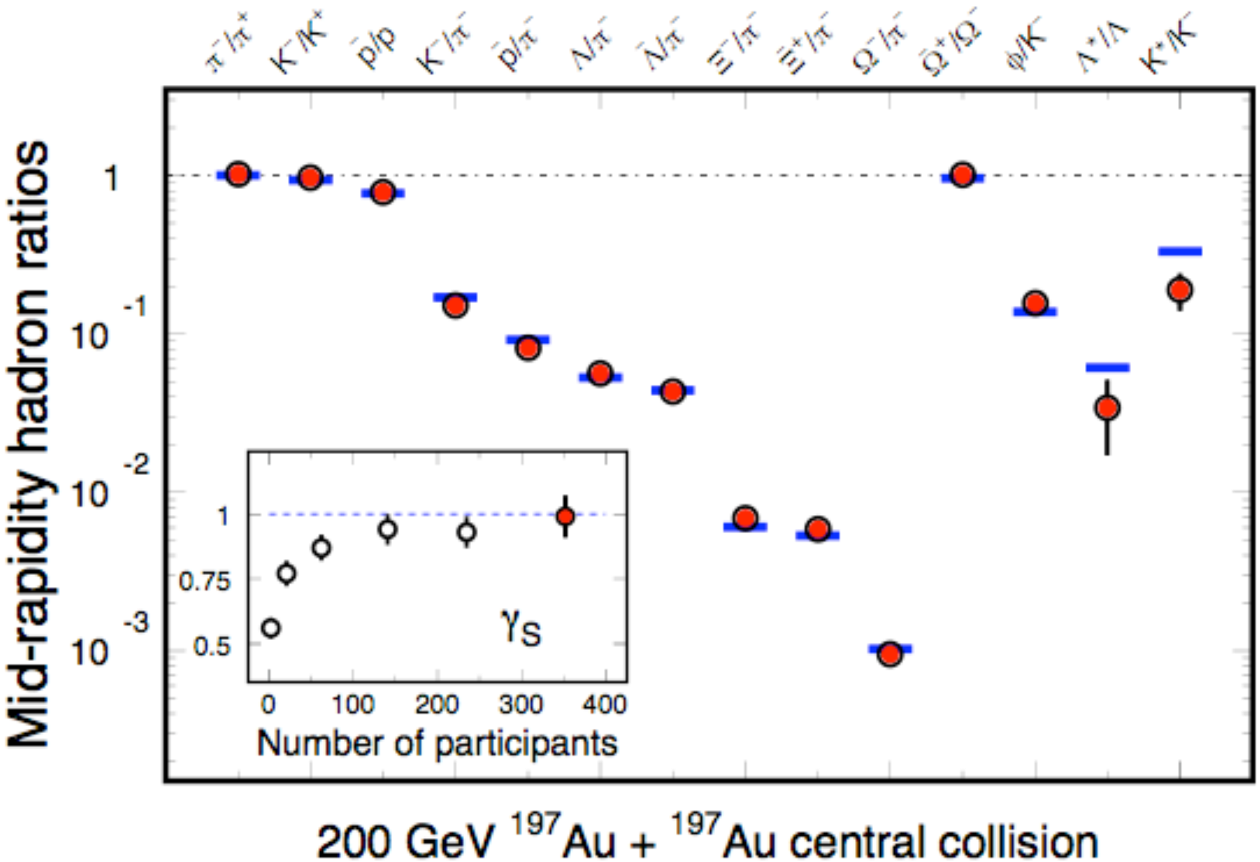
Hadron spectra from RHIC

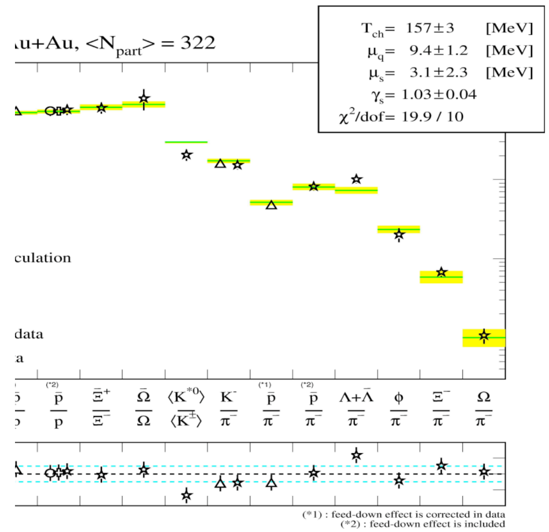
p+p and Au+Au collisions at 200 GeV



White papers - STAR: Nucl. Phys. A757, p102;

Ratio analysis

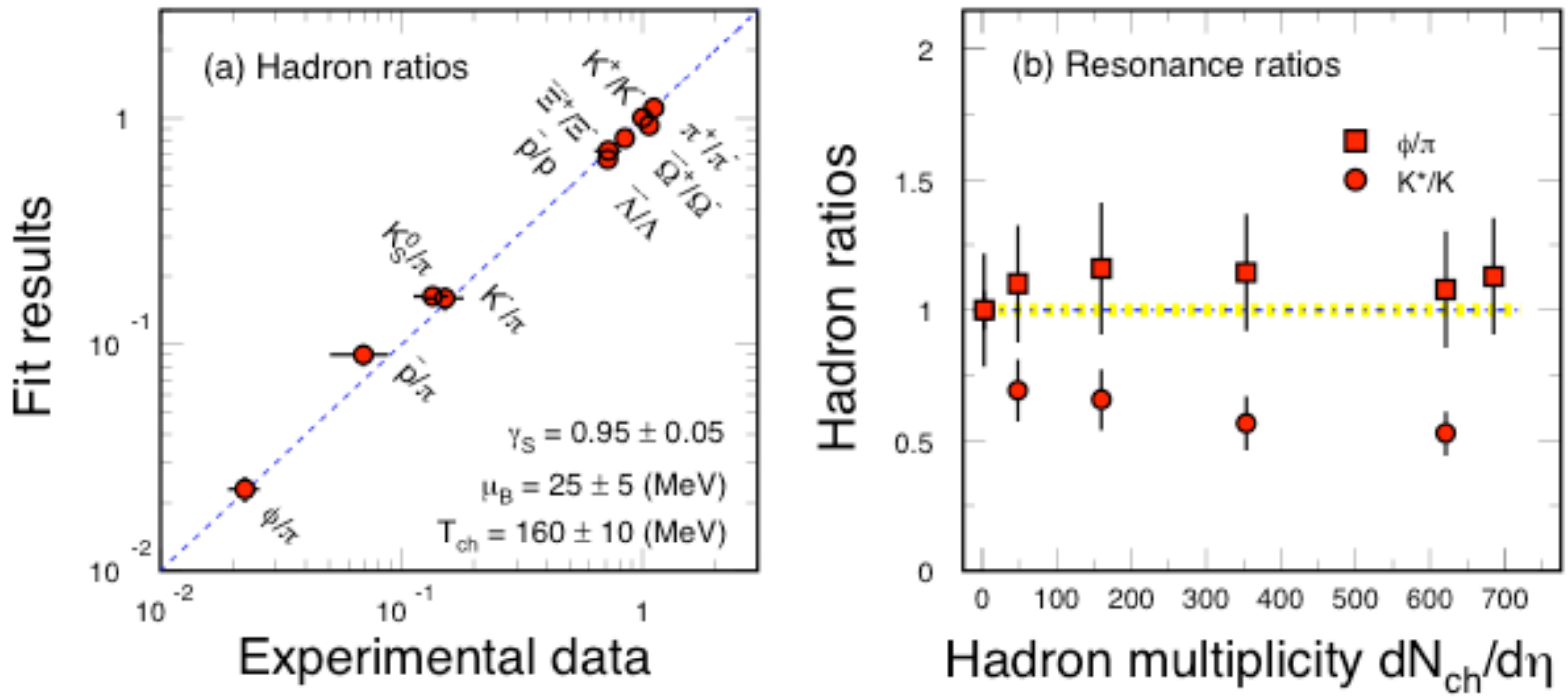




In central collisions, thermal model fit well, $\gamma_S = 1$.

White papers - STAR: Nucl. Phys. *A757*, p102; PHENIX: p184(2005)

Hadron ratios



Chemical fit to data but not for short lived resonances
-- *there is life after chemical freeze-out*!

Summary for the ratio analysis

1) At RHIC, gluons are abundant and strange hadrons are copiously produced.

2) Thermal model fits works well in fitting the hadron ratios. **The system is thermal.** However, we do not know how does the system approach the observed equilibrium in high-energy nuclear collisions. Once the status of the thermalization is established, the 'historical' dynamics has lost in the integrated yields and ratios.

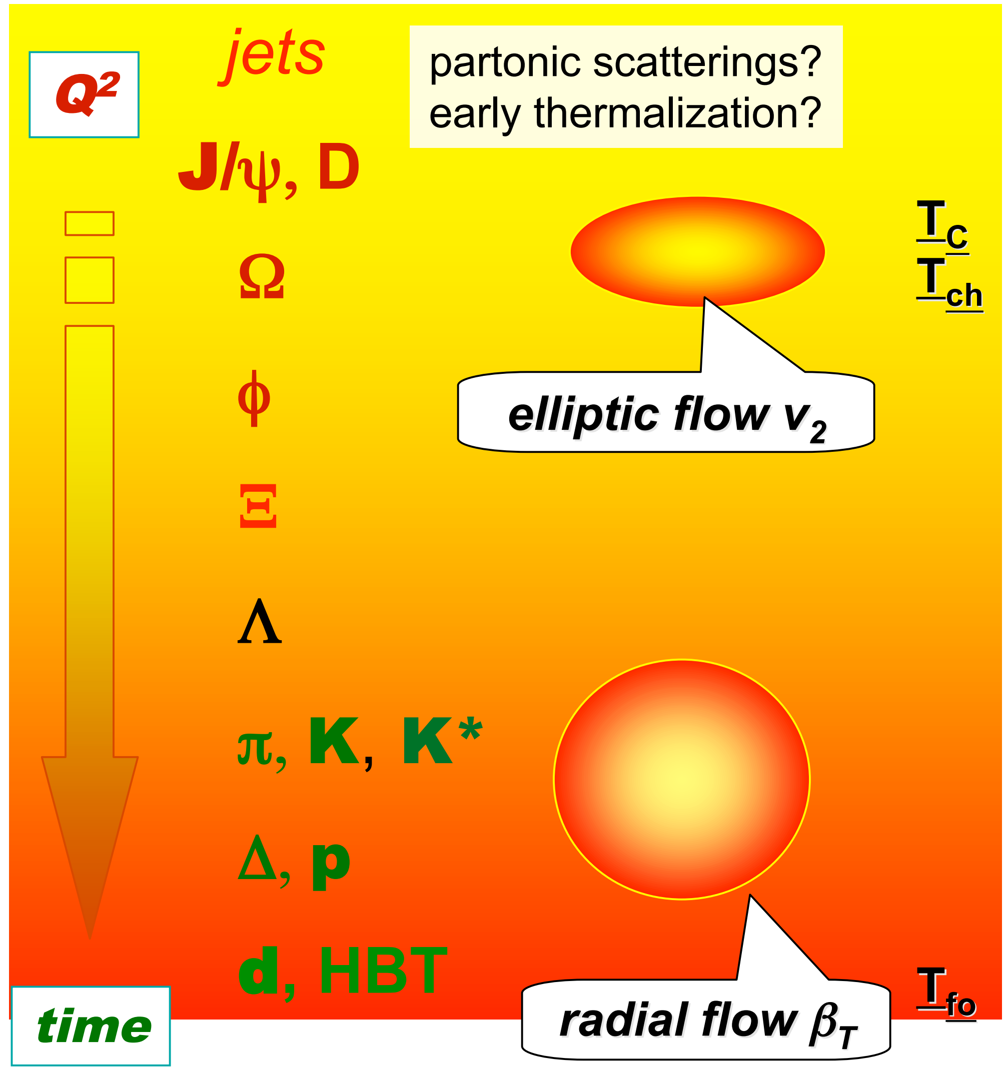
3) Transverse motion is 'created' during the collisions. Thermal dynamic parameters extracted from the transverse momentum spectra, event anisotropy and other distributions are useful for analyzing the dynamical history.

High-Energy Nuclear Collisions

Initial Condition
- initial scatterings
- baryon transfer
- E_T production
- parton dof

System Evolves
- parton interaction
- parton/hadron expansion

Bulk Freeze-out
- hadron dof
- interactions stop



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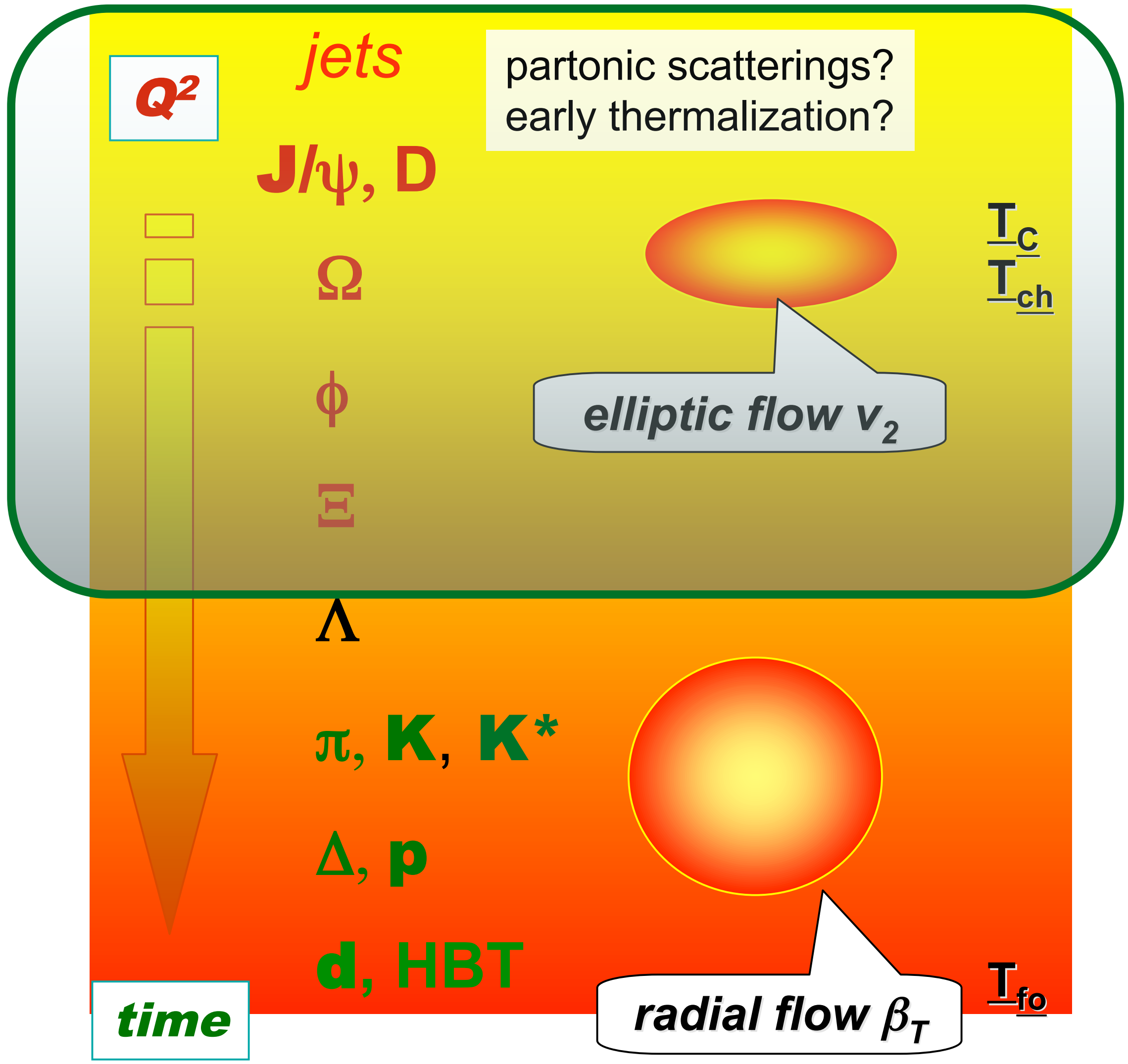
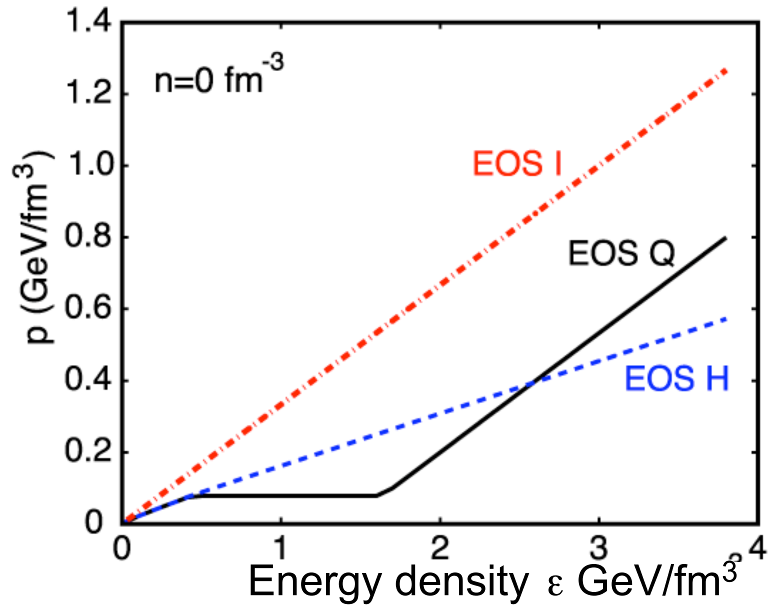


Equation of State

$$\partial_\mu T^{\mu\nu} = 0$$

$$\partial_\mu j^\mu = 0 \qquad j^\mu(x) = n(x) u^\mu(x)$$

$$T^{\mu\nu} = [\varepsilon(x) + p(x)] u^\mu u^\nu - g^{\mu\nu} * p(x)$$



EOS - the system response to the changes of the thermal conditions - is fixed by its ***p*** and ***T*** (ε).

Equation of state:

- **EOS I** : relativistic ideal gas: $p = \varepsilon/3$
- **EOS H**: resonance gas: $p \sim \varepsilon/6$
- **EOS Q**: Maxwell construction: T_{crit}= 165 MeV, $B^{1/4}$ = 0.23 GeV ε_{lat}=1.15 GeV/fm^3

P. Kolb et al., Phys. Rev. ***C62***, *054909 (2000).*

Physics Goals at RHIC

Identify and study the properties of matter with partonic degrees of freedom.

Penetrating probes

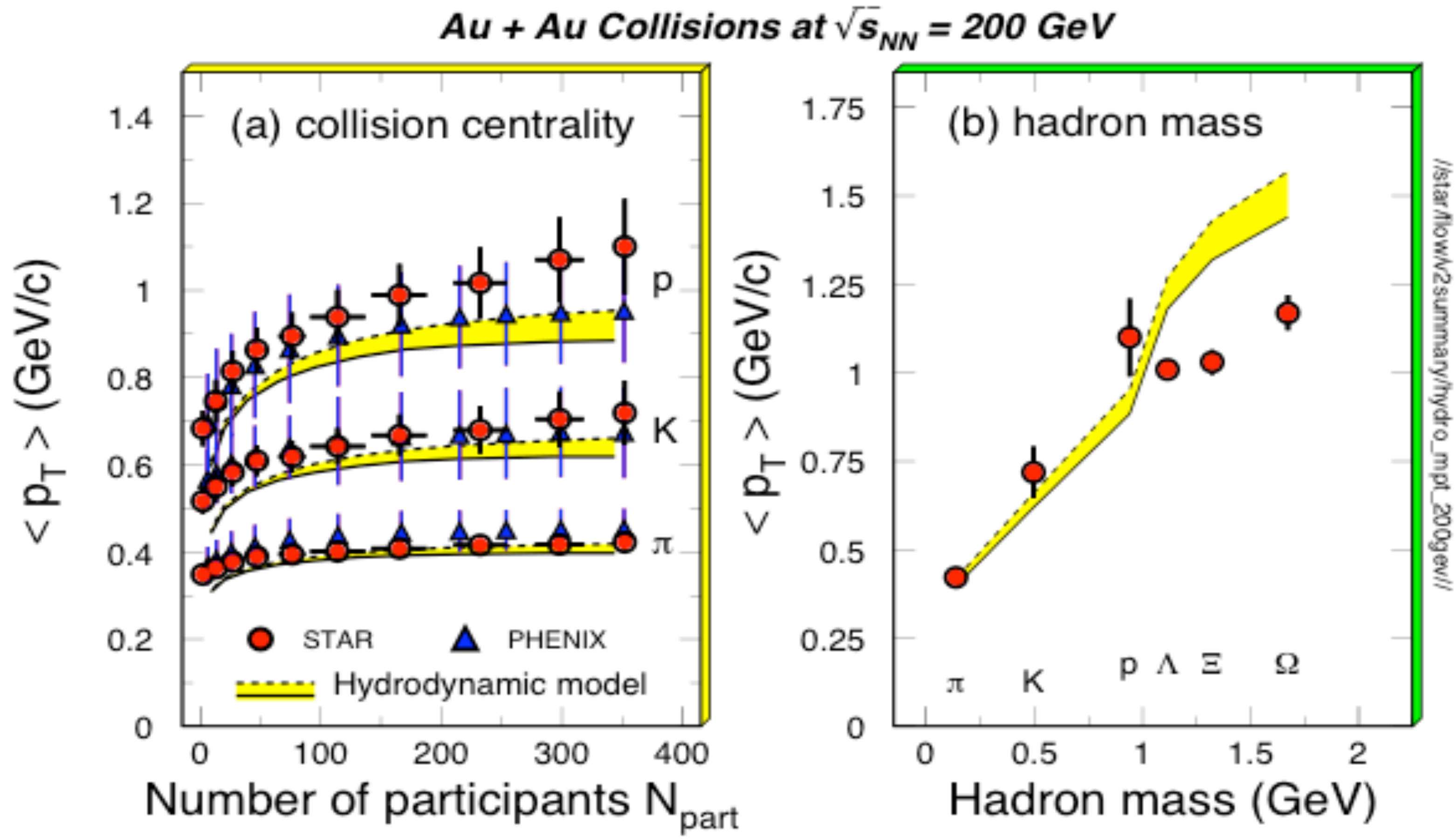
- direct photons, leptons
- “jets” and heavy flavor

Bulk probes

- spectra, v_1, v_2 …
- partonic collectivity
- fluctuations

Hydrodynamic Flow = Collectivity $\otimes$ Local Thermalization

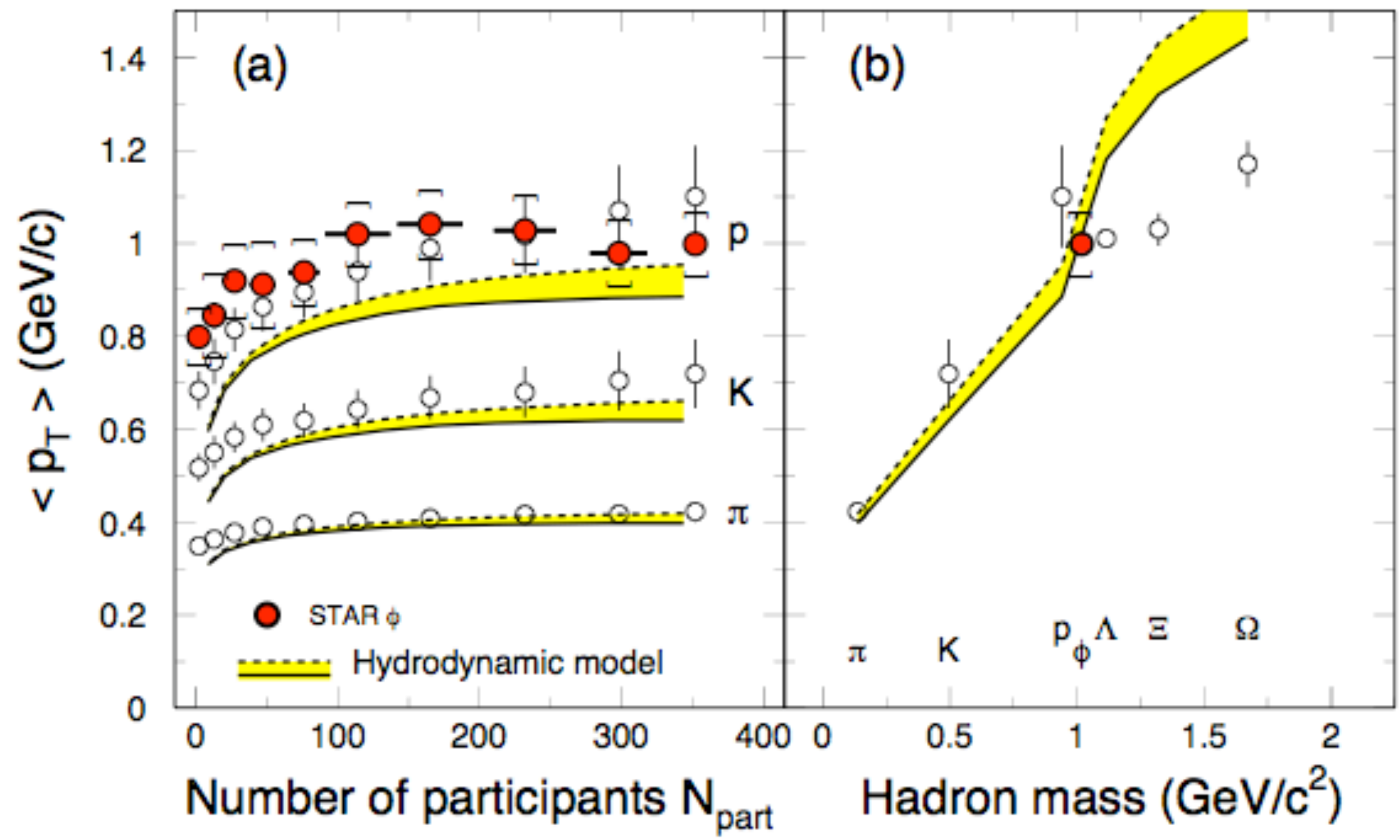
Compare with hydro-model results



This model results fit to pion, Kaon, and proton spectra well, but over predicted the values of $<p_T>$ for multi-strange hadrons

(T_C=165 MeV, T_{fo}=100 MeV +…) *P. Kolb et al., Phys. Rev.* ***C62****, 054909 (2000).*

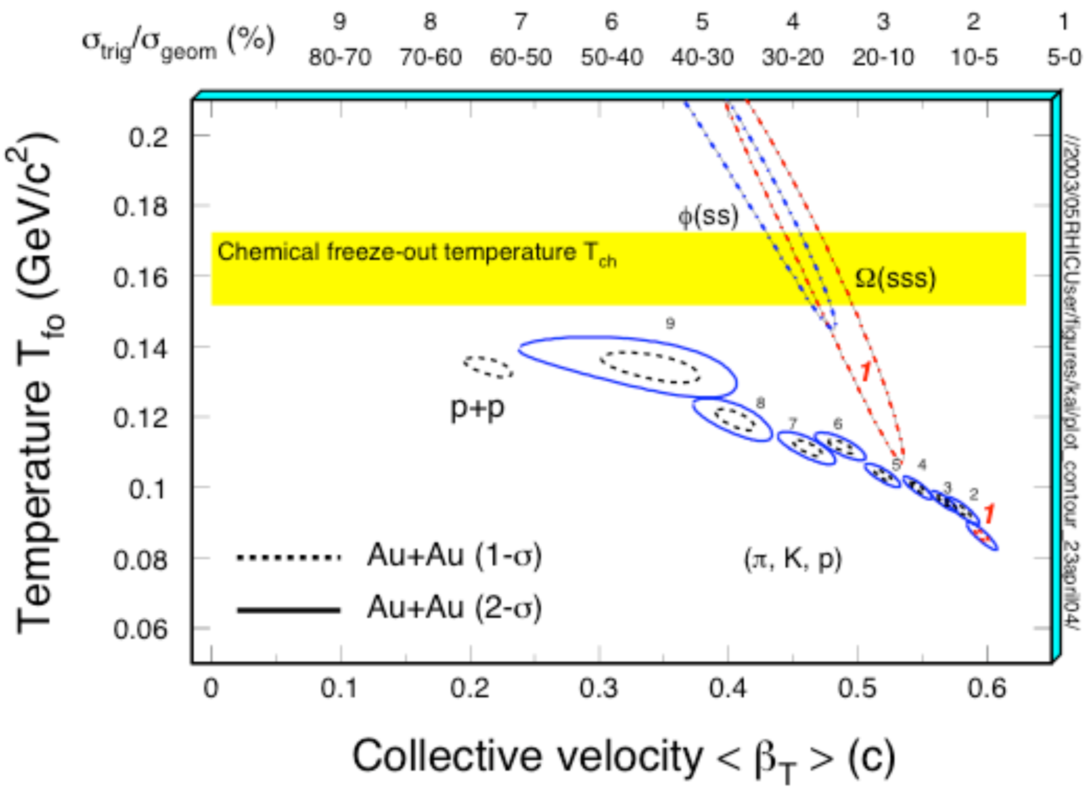
φ results



φ mean p_T almost flat versus collision centrality
The mechanism for φ-meson production still a puzzle

Blast wave fits: T_{fo} vs. $< \beta_T >$

200GeV Au + Au collisions



1) π, *K*, and *p* change smoothly from peripheral to central collisions.

2) At the most central collisions, $<\beta_T>$ reaches 0.6c.

3) Multi-strange particles ϕ, Ω are found at higher T and lower $<\beta_T>$

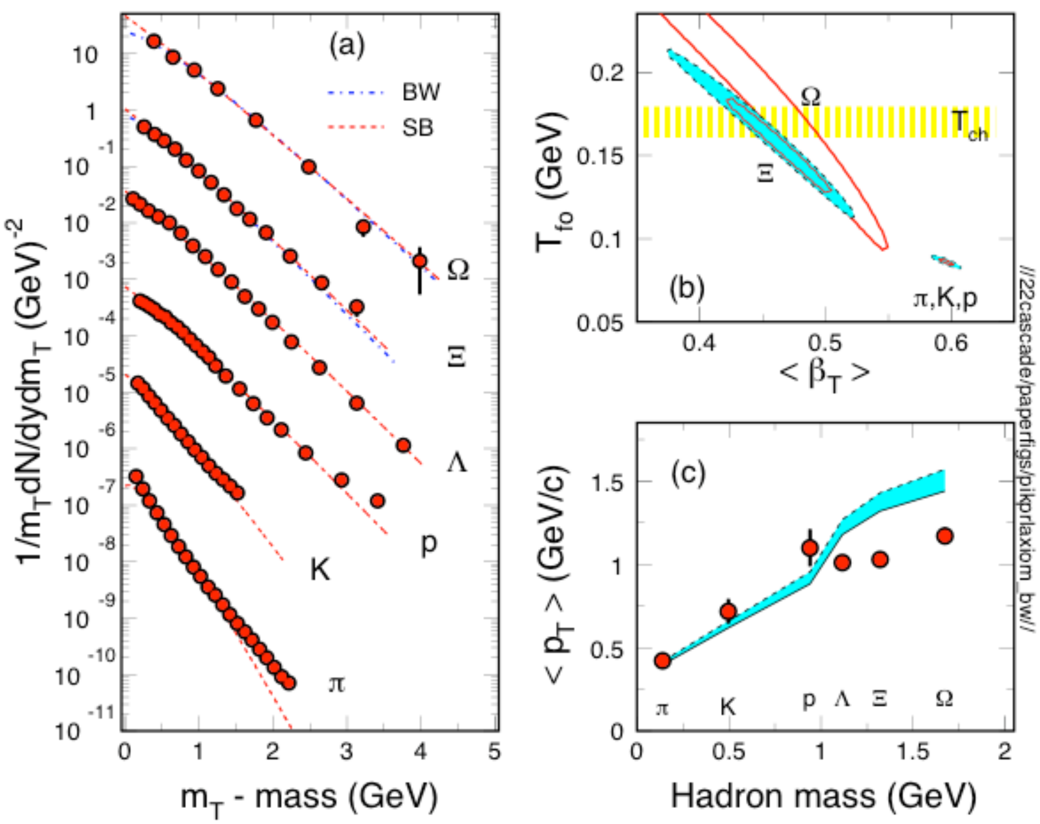
➪ **Sensitive to early partonic stage!**

➪ **How about v_2?**

STAR: NP**A715**, 458c(03); *PRL* ***92***, *112301(04);* ***92***, *182301(04).*

Early freeze-out

Central Au+Au collisions at RHIC



1) Multi-strange hadrons seem to freeze out earlier than others ➪ sensitive probe for early dynamics

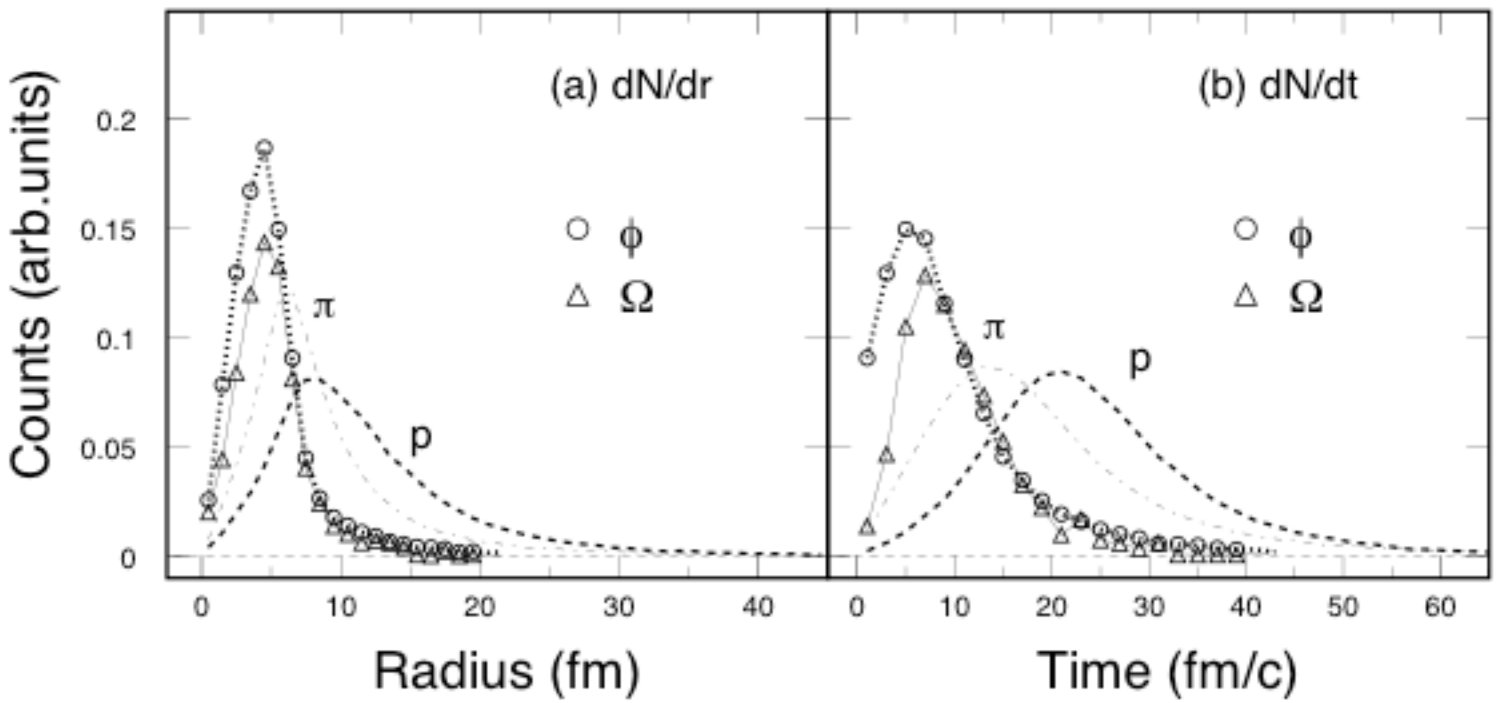
2) Charm-hadrons should be better. A possible complication is the pQCD hard spectrum.

3) J/ψ coalescence/melting: a tool for early dynamics CGC, deconfinement, and thermal equilibrium

*PHENIX: Phys. Rev. **C69** 034909 (04).*
*STAR: Phys. Rev. Lett. **92**, 112301(04);*
*Phys. Rev. Lett. **92**, 182301(04).*
*A. Andronic et al., NP**A715**, 529(03).*
*P. Kolb et al., Phys. Rev. **C67** 044903(03)*

Chemical Freeze-out: inelastic interactions stop
Kinetic Freeze-out: elastic interactions stop

Tests with hadronic transport model

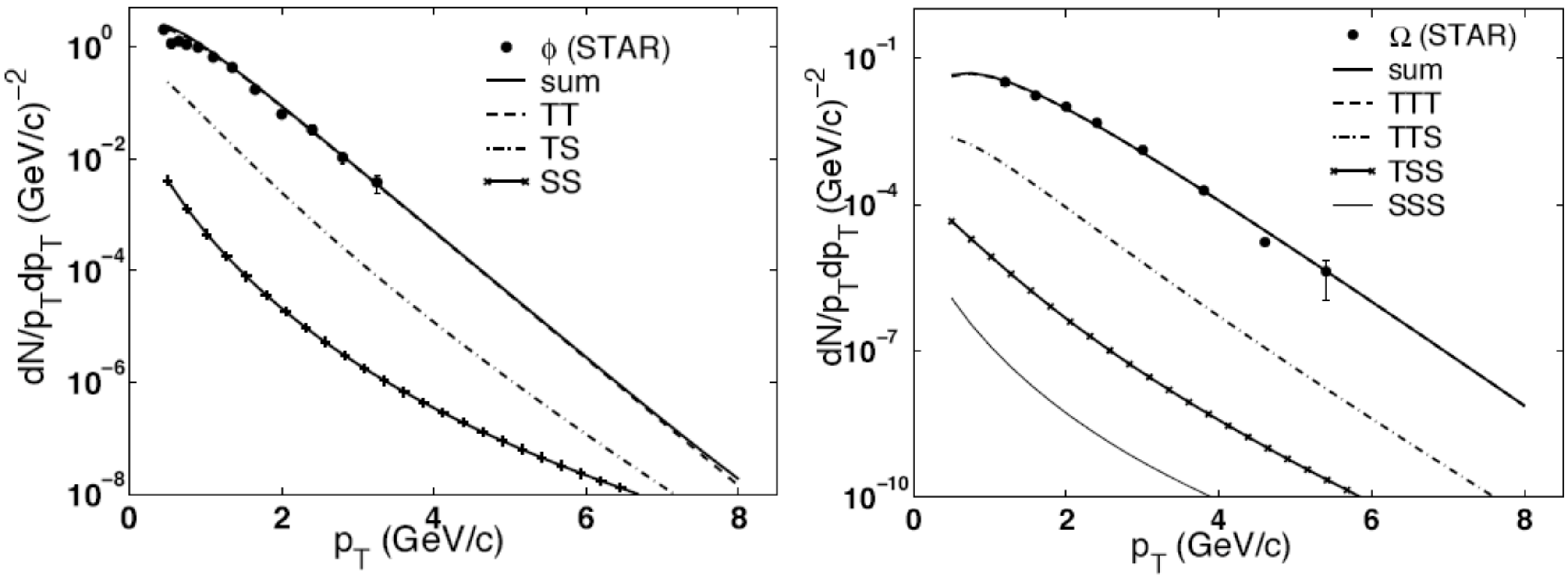


In hadronic interactions, multi-strange hadrons freeze-out earlier than π, K, p!

H. van Hecke et al. Phys. Rev. Lett. **81**, 5764(98)
Y. Cheng et al., Phys. Rev. **C68**, 034910(03).

Coalescence approach

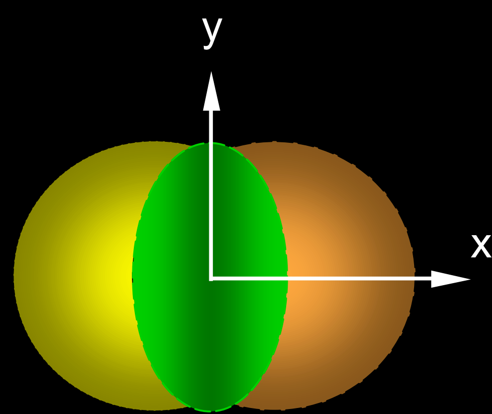
R. C. Hwa and C.B. Yang, nucl-th/0602024

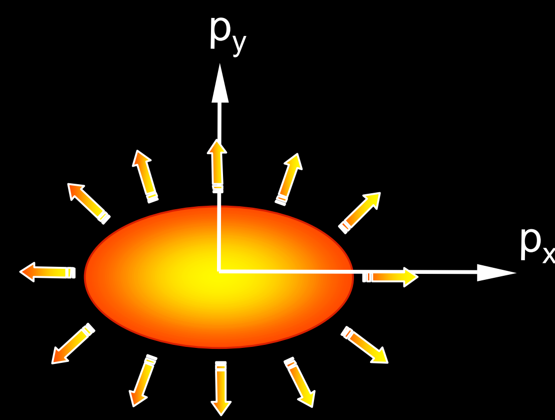


STAR data: central Au+Au collisions
- Flow developed at partonic stage, suppressed
- Hard contribution to hidden-strangeness hadron production is suppressed
- $K^+ + K^- \neq> \phi$, see STAR paper ***PLB612***, 181(05)

Anisotropy Parameter v_2

coordinate-space-anisotropy ⇨ momentum-space-anisotropy

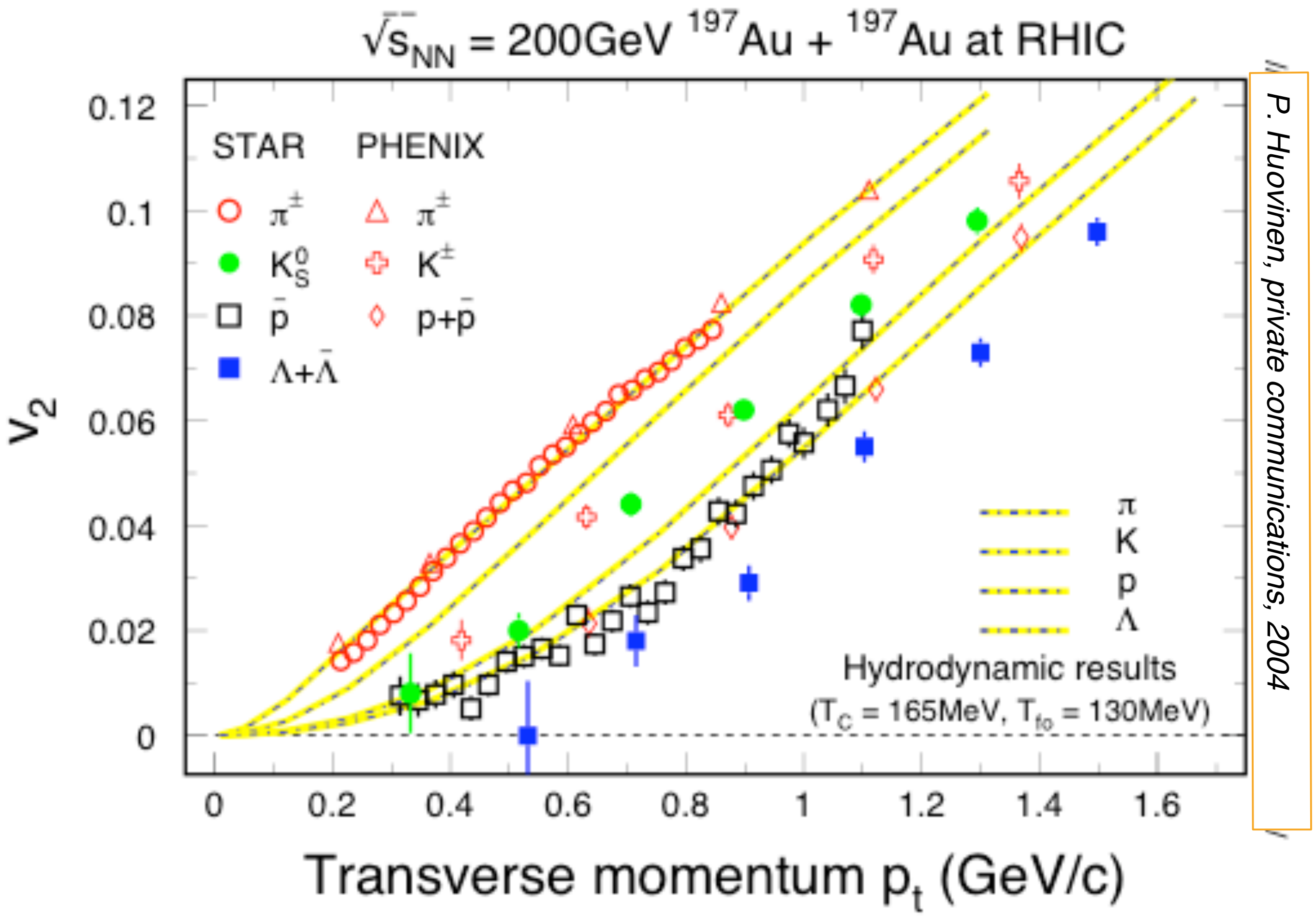




$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle} \qquad v_2 = \langle \cos 2\varphi \rangle, \quad \varphi = \tan^{-1}\left(\frac{p_y}{p_x}\right)$$

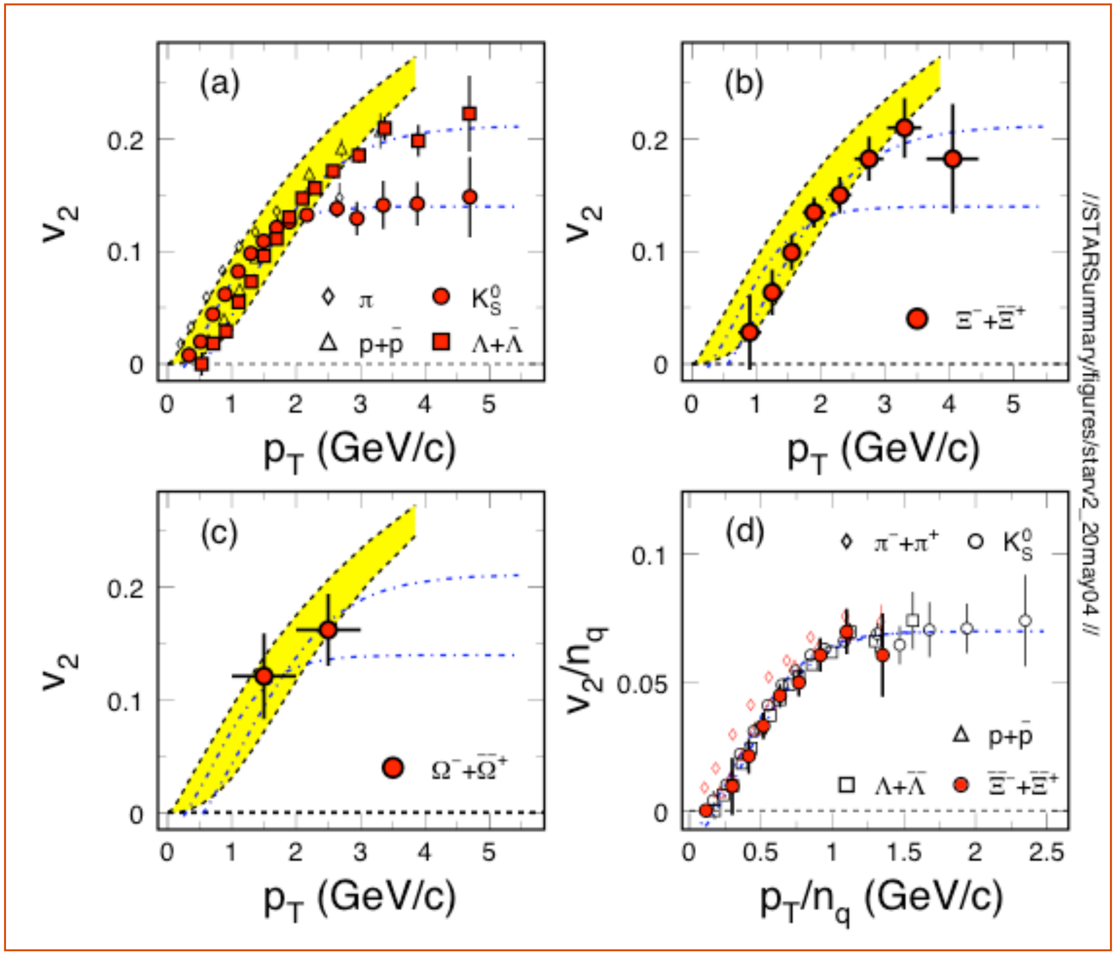
Initial/final conditions, EoS, degrees of freedom

v_2 at low p_T region



- Minimum bias data! At low p_T, model result fits mass hierarchy well!
- Details does not work, need more flow in the model!

Collectivity, Deconfinement at RHIC



- v_2, spectra of light hadrons and multi-strange hadrons
- scaling of the number of constituent quarks

At RHIC, I believe we have achieved:

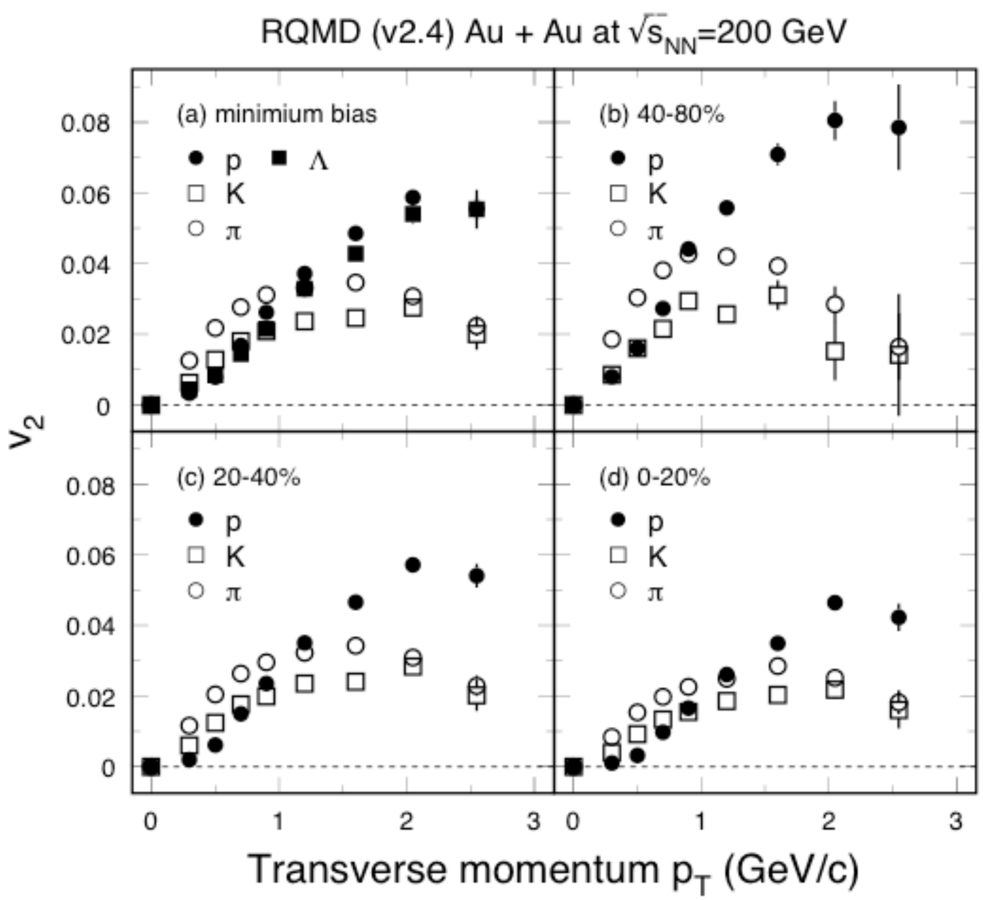
➪ **Partonic Collectivity**

➪ **Deconfinement**

*PHENIX: PRL**91**, 182301(03)*
*STAR: PRL**92**, 052302(04), **95**, 122301(05) nucl-ex/0405022*

S. Voloshin, NPA715, 379(03)
*Models: Greco et al, PR**C68**, 034904(03)*
*X. Dong, et al., Phys. Lett. **B597**, 328(04).*
….

However, hadronic transport …



RQMD results show the particle type dependence although the absolute amplitudes of v_2 are a factor of 2 or so too small!

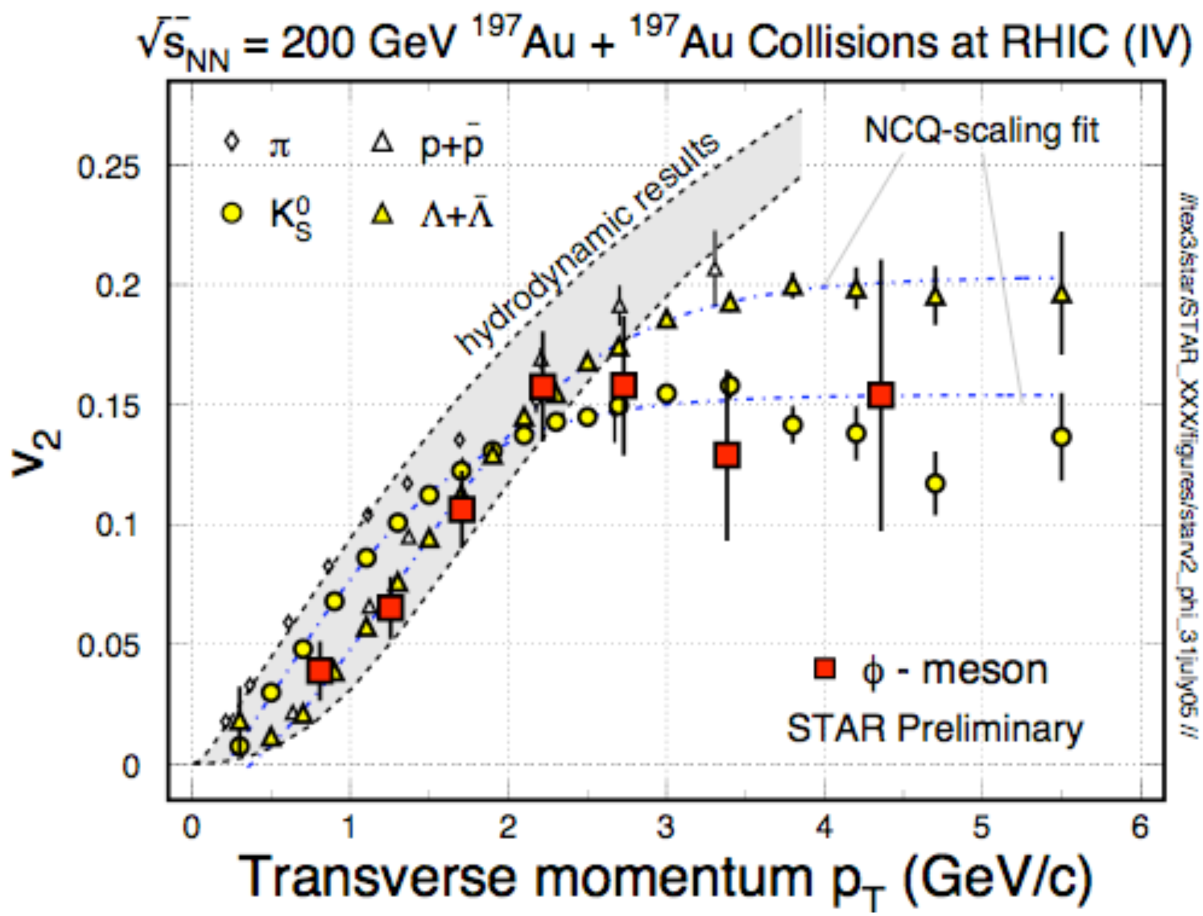
1) At low p_T region: mass ordering - feature of hydrodynamic motion

2) Hadron type dependence at the intermediate p_T region - vacuum hadronic cross sections used in the model

3) The number of constituent quark scaling may not be unique!

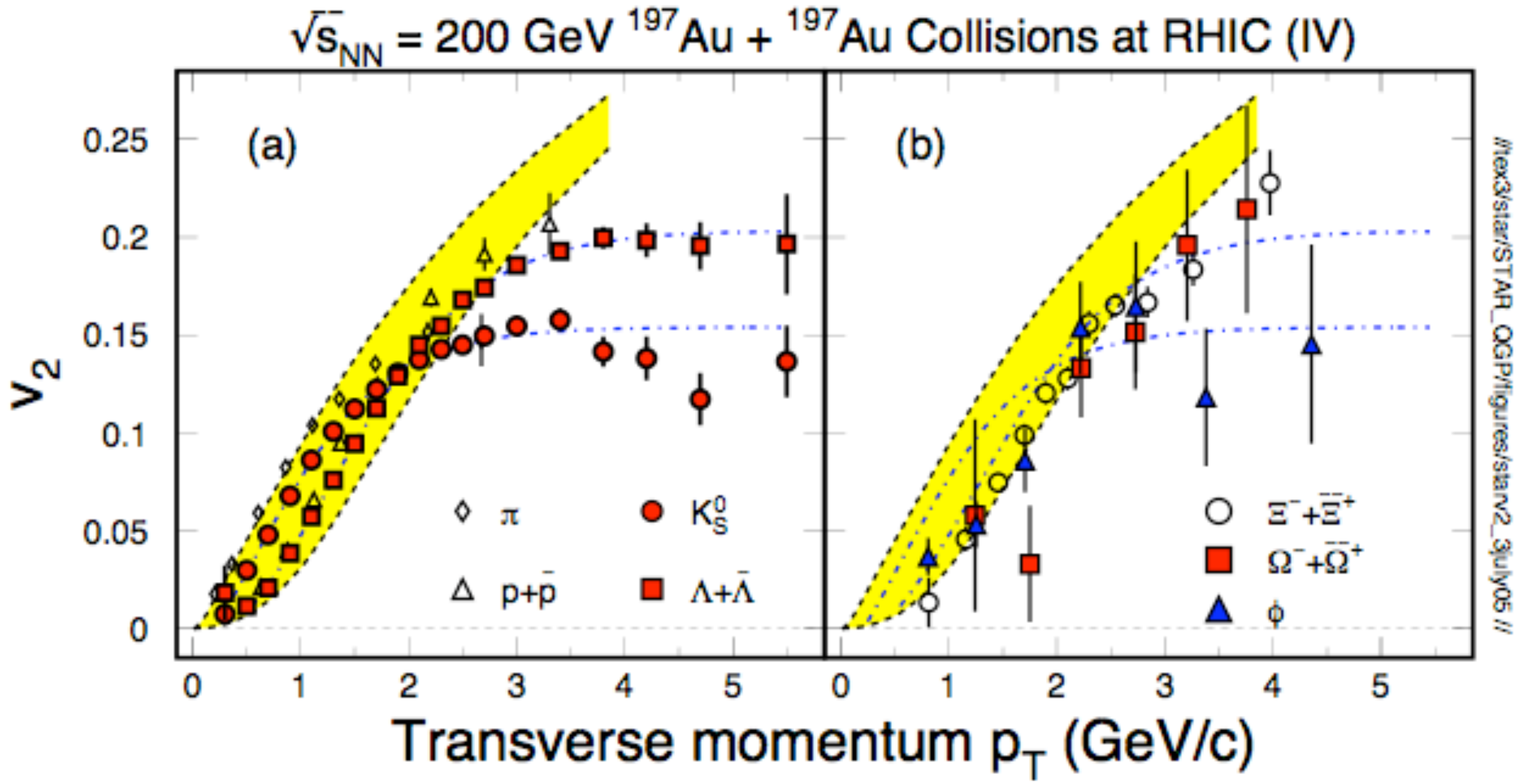
Y. Lu *et al.*, nucl-th/0602009

ϕ-meson flows



STAR Preliminary, QM05 conference

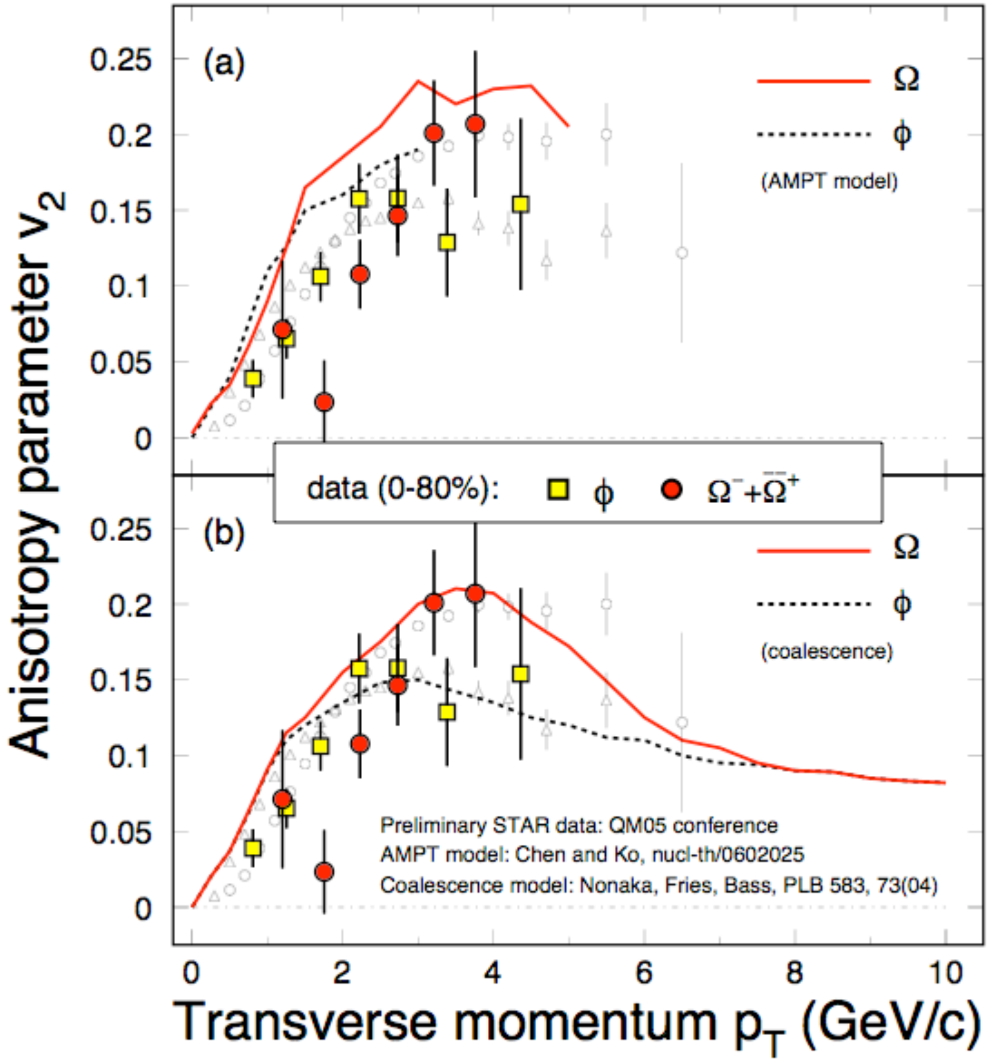
v_2 of multi-strange hadrons



'Strangeness' flows - partonic collectivity at RHIC!

STAR Preliminary, QM05 conference

Dynamic model results



Models seem to work in $2.5 < p_T < 5$ GeV/c

In those models, almost no interactions at the late hadronic stage. Flow has developed prior to hadronization:

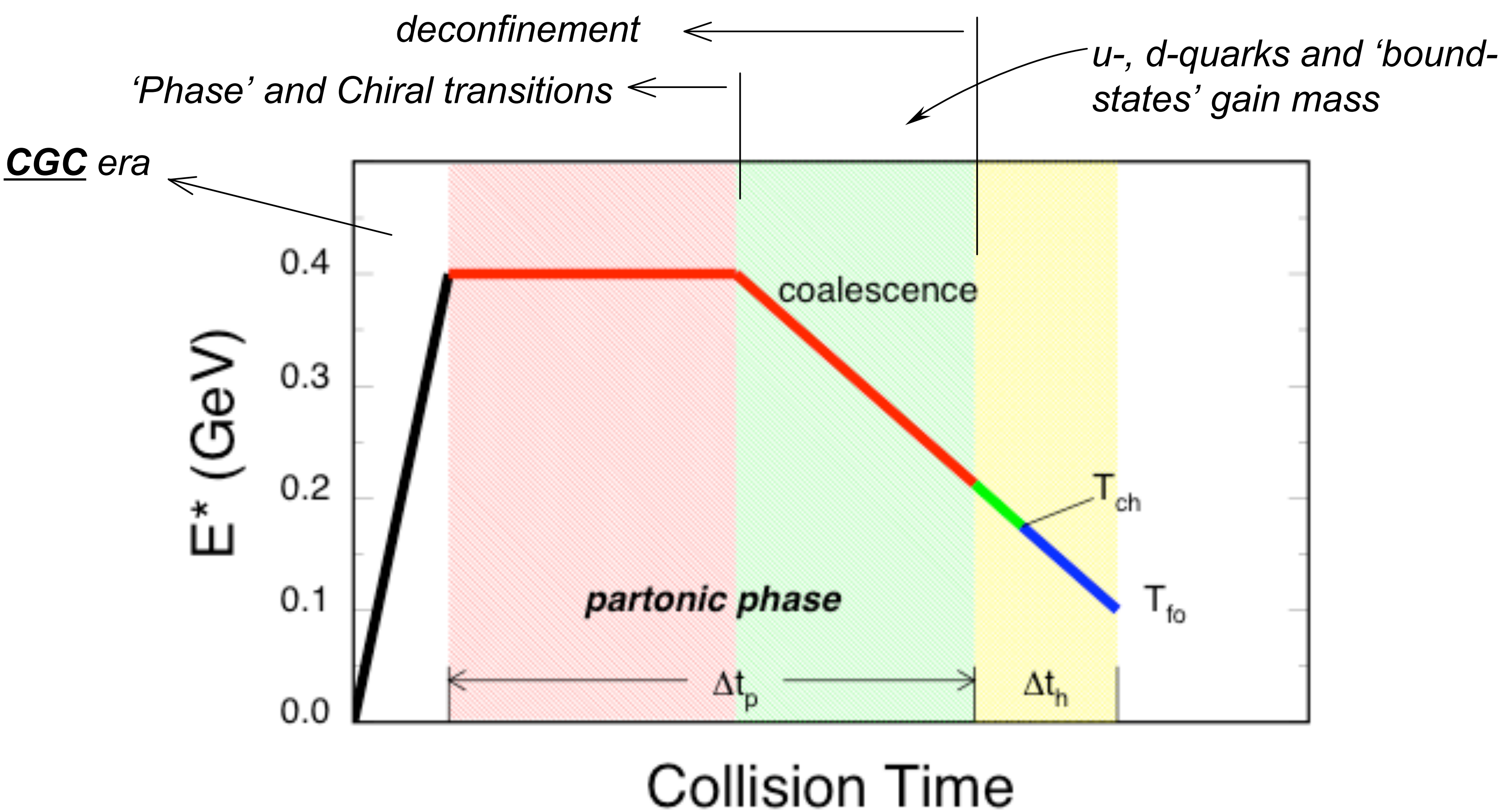
⇒ **partonic collectivity**

⇒ **indication of de-confinement**

“BUT: Elliptic flow pattern is approximately additive in valence quarks, reflecting partonic, rather than hadronic origin of flow.”

B. Muller, May 2005

Collision Time - a picture for RHIC



1) *Coalescence processes occur during phase transition and hadronization;*
2) *The u-,d-quarks and 'bound-states' gain mass accompanied by expansion;*
3) ***Early partonic thermalization and its duration need to be checked.***

Summary and outlook

- Strangeness production and dynamics play important role for understanding the hot/dense medium at RHIC

- The experimental results on spectra and v_2 measurements, **especially with the multi-strange hadrons**, have clearly demonstrated the development of partonic collectivity at RHIC. An important step towards the fixing EOS at RHIC!

Open issues

- Measure the partonic velocity to infer pressure parameter - important for mapping the EoS at RHIC
- Understand the meson and baryon difference in p+p collisions - more non-biased p+p data should be collected at RHIC
- Resonance v_2 measurements are needed to understand the number of constituent quark scaling AND the activities in the later hadronic period
- In order to demonstrate the possible early partonic thermalization, we are pushing for the heavy flavor collectivity measurement - RHIC heavy flavor program
- In order to demonstrate the possible phase transition, we should push for the energy scan program at RHIC!